BATTERY CHARGING WITH A SMALL DOWNWIND HORIZONTAL-AXIS WIND TURBINE

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ABSTRACT

Testing was initiated in Jan 2002 on a small wind turbine designed for battery charging which used a uniquely designed furling system. This downwind horizontal-axis wind turbine furls by the tail lifting the rotor and alternator from a blade rotor horizontal-axis position to a blade rotor vertical-axis position (e.g. similar to a helicopter) at moderately high wind speeds. For Bushland, TX elevation -- 1159 m (3800 ft), the wind turbine began furling at a 13.5 m/s wind speed and would be fully furled for wind speeds above 20 m/s. This 3.5-m diameter wind turbine had a cut-in wind speed of 3 m/s and power peaked at 830 Watts (corrected to sea level, standard day conditions) at a wind speed of 13.5 m/s. For a Rayleigh wind distribution with a mean wind speed of 4.5 m/s, this wind turbine generated 4.1 kWh/day (AC power) or 3.2 kWh/day (DC power) at Bushland, TX.

INTRODUCTION

Because wind and solar energy are intermittent resources, many small renewable powered energy systems use batteries for storing energy in order that power can be provided when the wind is not blowing or the sun is not shining. However, renewable energy systems that pump water do not require batteries since the water can be stored instead of the electricity. There are other options available that don't involve batteries including using a backup fossil-fuel generator or using fuel cells. The battery bank is usually sized for the longest number of days expected without sun for a solar system and longest number of days of no wind for a wind system. The deep cycle batteries used in renewable energy systems usually have a long life if they are maintained properly – no excessive discharging, no over charging, kept in a cool dry place, not sitting on cement.

The USDA-ARS Conservation and Production Research Laboratory (CPRL) near Bushland, TX has been testing the Synergy Power Corporation[1] (www.synergypowercorp.com) S5000DD wind turbine for 1.5 years. The main headquarters for Synergy is in Hong Kong, but the wind turbine and controller were manufactured in Malaysia. The turbine is sold in the U.S. through a U.S. office. Planned testing for this wind turbine includes: powering DC electrical loads with batteries, powering AC electrical loads via an inverter, and pumping water using variable voltage/frequency 3-phase electricity directly from the wind turbine.

Using a small wind turbine with a permanent magnet alternator (PMA) which generates 3-phase variable voltage/frequency AC electricity to charge batteries requires a more complex controller than that needed for solar-PV or small wind turbines with DC generators. Therefore many papers in the literature have been written on optimizing the wind turbine PMA output for charging batteries [1-5]. The National Renewable Energy Laboratory (NREL) has been evaluating various small wind turbines over the past several years using their battery charging station (6, 7, 8, 10). Some researchers in Australia have used a wind turbine with an induction generator for charging batteries [9].

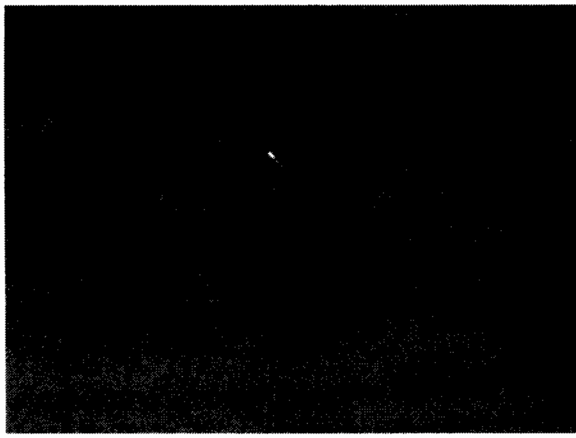
In the battery charging testing at CPRL with the S5000DD wind turbine, we analyzed the effect of changing the DC electrical loading of the load bank. The electrical loading consisted of strings of lights (resistive) where the electrical loading could be varied between 4 and 16 amps in increments of 4 amps. Assuming a battery voltage of 50 V, the range in load power was 200 to 800 W.

DESCRIPTION OF WIND-ELECTRIC BATTERY CHARGING SYSTEM

The Synergy S5000DD wind turbine was a 3-bladed 3.5-m diameter downwind horizontal-axis wind turbine with a tail (Figure 1). The tail was used for over speed protection by lifting the wind turbine to a vertical-axis position (Figure 2) -- similar to a helicopter in hover. The fins on the tail were an airfoil shape and were needed to counter-balance the torque of the wind turbine rotor in the furled (helicopter) position. The tail fins are also used to provide some yaw damping and yaw alignment assistance. The PMA for this wind turbine was wound for either a 24 or 48-Volt battery charging system. Testing at Bushland began with the 24-Volt PMA, but it was decided that the 48-Volt PMA would be used since Synergy didn't sell many 24-Volt PMA systems. All test results shown in this paper were collected with the 48-Volt PMA.

The battery charging controllers for this wind turbine also come in 24 and 48-Volt models, but both operate similarly. It is important to always have a battery bank connected to the controller when the wind turbine is operating, otherwise the controller will not function correctly. There is a brake switch (connects three phases together from the wind turbine) on the controller box for stopping the wind turbine at low wind speeds. This controller prevents overcharging by connecting the wind turbine to some inductors when the battery voltage reaches a certain level (56 V for 48-V controller). In case there is a charging failure or the wind turbine goes into over speed, the controller will switch the power from the wind turbine to a (resistive) dump load located outside the controller box. The controller does not provide protection against excessive

[1] The mention of trade or manufacture names is made for information only and does not imply an endorsement, recommendation, or exclusion by USDA – Agricultural Research Service.



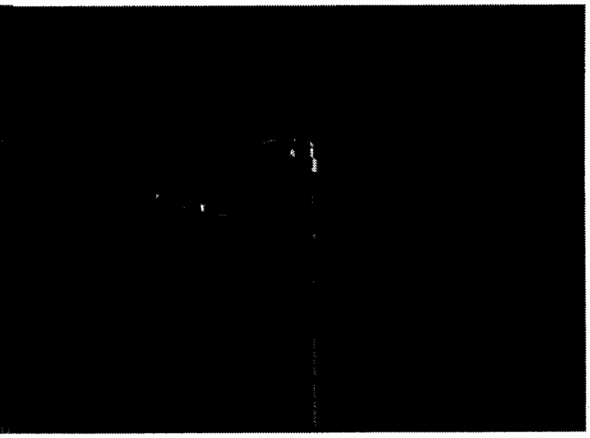


Figure 1. Synergy S5000DD Wind Turbine (Wind Speed < 13 m/s).

Figure 2. Synergy S5000DD Wind Turbine (Wind Speed = 18 m/s).

discharge of the batteries. Agricultural Research Service/ Alternative Energy Institute (ARS/AEI) personnel installed a switch between the controller and the batteries, so during significant downtimes (more than 2 weeks) the controller would not discharge the batteries. The current dissipated by the controller in the brake-off position is 0.21 A (5 A-h per day) and in the brake-on position was 0.39 A (9.4 A-h per day). ARS/AEI personnel also installed a voltage (high / low) relay between the batteries and the electrical load in order to keep the electrical load from discharging the batteries excessively. A timer switch was also installed between the batteries and the electrical load (lights) which could switch the electrical load on during different times of the day and different days of the week.

The batteries used for this testing were four 12-volt lead-acid gel-cell batteries connected in series (48 Volts). Besides not requiring any maintenance, these batteries usually have a long life as long as they are not over charged or discharged excessively. Each battery was rated at 98 A-h for discharging over a 100-hour period (e.g. 1 A) and 86 A-h for a 20-hour discharging period (e.g. 4.3 A). The batteries were kept in a climate controlled building. During a period of approximately four weeks in May-June of 2002, the batteries completely discharged due to the power requirements of the controller. This resulted in four new lead acid gel-cell batteries having to be purchased. . A disconnect switch was installed between the controller and the batteries, and no further problems have been experienced with the new gel-cell batteries, and they have been operating for over a year now.

The load bank for this battery charging system consisted of 16 incandescent light bulbs – each rated at 12 V and 50 W. There were four sets of four bulbs connected in series and there were manual switches which connected each string of lights in parallel. Each string of lights would pull approximately 4 A (exact current depends on battery voltage) from the batteries.

DESCRIPTION OF INSTRUMENTATION AND DATA ACQUISITION SYSTEM

The data collected on the wind turbine battery charging system included:

1. Wind speed (m/s)
2. Wind direction (degrees)
3. Wind turbine AC power (W)
4. Wind turbine frequency (Hz)
5. Wind turbine AC voltage (V)
6. DC battery voltage (V)
7. DC charging current (A)
8. DC load current (A)

Before the wind turbine was installed, a Met One[1] anemometer (Model 014) was mounted on the top of the wind turbine tower (at hub height). Another Met One anemometer was also installed on the wind turbine tower at a 13.7-m height. Data from an existing Met One anemometer on a tower located about 120 m WNW of the wind turbine was also recorded on the Campbell 23X data logger. Approximately 3 weeks of data were collected on these three anemometers and compared. The 19.5-m height anemometer (hub height of wind turbine) was 0.55 m/s higher in wind speed than the 13.7-m height anemometer and 0.25 m/s higher than the 15.2-m height anemometer. When the wind turbine was installed, the wind speeds measured by the two anemometers (13.7 m and 15.2 m heights) were corrected to hub height and stored on the data logger. A Climet[1] anemometer (Model 011) could measure one-second wind speed data accurately, so it was used to replace the Met One anemometer on the tower. The plastic cups of the Climet anemometer (Met One uses metal cups) would break off after approximately four weeks of vibration of the tower by the wind turbine, so it has been replaced by an R. M. Young[1] ultrasonic anemometer (Model 81000). The wind direction was obtained from another data acquisition system until the R. M. Young anemometer was installed – this anemometer records wind speed, horizontal wind direction, and vertical wind direction. To correct the power data to sea level, standard day (SLSD) conditions, air density was obtained from another data acquisition system. The instrument used for measuring AC power was an Ohio Semitronics[1] (Model P-144X5). AEI personnel built the wind turbine frequency transducer. The DC battery voltage was measured by a Flex-core VT7-004X5. The transducer used for measuring the wind turbine AC voltage was a Rochester Instruments[1] (Model VCC-1B). The transducers used for measuring the charging and load DC current were Flex-core CTG-101SX5's.

All the instrumentation data were recorded on a Campbell Scientific Instruments[1] (CSI) 23X data logger. The data was sampled every second and the average value was stored every minute. When the wind speed measured by the wind turbine tower anemometer exceeded 9 m/s, the wind speed, wind direction, frequency, and AC power would be recorded every second. This one-second data was mainly collected in case there was a failure of the wind turbine. so the conditions (wind speed, rotor rpm, wind direction, AC power) before failure would be known. The data from the data logger was stored on a CSI storage module (Model SM4M). At least once a week the data would be downloaded from the storage module to a PC computer. These data would be divided into days with a computer program that binned the data in 0.5 m/s bins.

RESULTS

Reliability of Wind-Electric Battery Charging System

The Synergy S5000DD wind-electric battery charging system has operated for about 1.5 years charging batteries and providing electricity for a load bank of 12-Volt, 50-Watt light bulbs. The only failure occurred on 5-8-2002 when the tail boom broke at the point where a structural member from the power head attaches to the tail boom. The reason for the failure was metal fatigue as a result of turbulence coming off a building up the hill to the north. The building in question is about 7 m tall and is 40 m away from the base of the wind turbine. While waiting for a new tail boom and tail from Synergy, the gel-cell batteries completely discharged due to the controller pulling power from the batteries. After getting a new set of batteries, a disconnect switch was installed between the controller and the batteries, so during down times the controller can be disconnected from the batteries.

Controller Operation

Two days will be shown to demonstrate the battery charging capability of this wind system:

1. A day when all the wind turbine electricity was used to charge the batteries and power the electrical load.
2. A day when the controller redirected part of the electricity from the wind turbine through inductors to keep the batteries from being overcharged.

Figures 3, 4, and 5 show a day (4-22-03) when all the electricity from the wind turbine was used to charge the batteries and power the DC load. The wind speed, wind turbine rotor speed, and the charging current are varying similarly during the entire day. From about 8:00 until 15:30 the charging current is exceeded the load current and during this time there is a steady increase in battery voltage. At 15:30 the load current was manually increased from 8 amps to 12 amps and the battery voltage drops from 53 Volts to 51.5 Volts. The charging and load current remain the same for the rest of the day, so the battery voltage remains constant. From the rate of increase in battery voltage during the 8 amp electrical loading, the controller would have redirected the wind turbine electricity through the inductors to prevent battery over charging if the load current hadn't been increased to 12 amps.

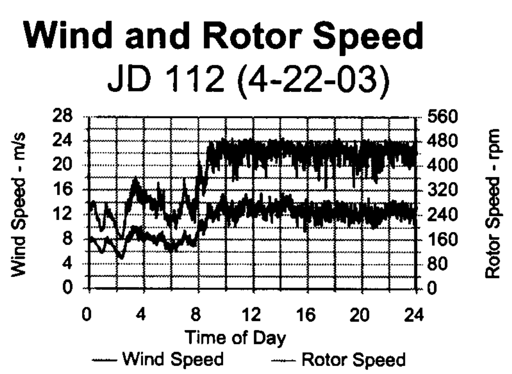


Figure 3. Wind Speed and Wind Turbine Rotor Speed (Apr. 22, 2003).

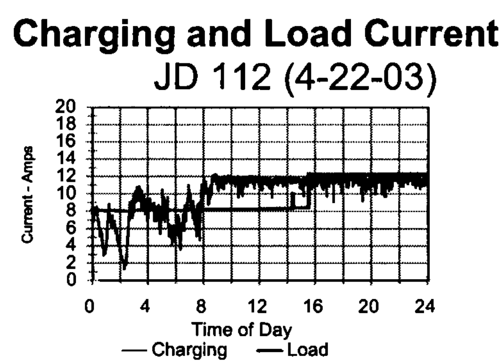


Figure 4. Charging and Load Current (Apr. 22, 2003).

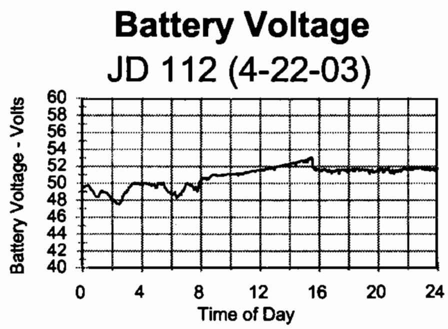


Figure 5. Battery Voltage (Apr. 22, 2003).

Figures 6, 7, and 8 show a day (12-1-02) when the controller redirected the electricity from the wind turbine to inductors in the controller (choke mode) to prevent the batteries from being overcharged. At 10:30, the battery voltage peaks at 56.5 Volts. Over the next 3 hours the charging current decreased to the level of the load current. The wind speed stayed high during this time and the charging current would have been high if the controller wasn't in choke mode. The battery voltage remains at 55 Volts until the wind speed decreased enough that the charging current dropped below the load current and the controller disconnected the inductors.

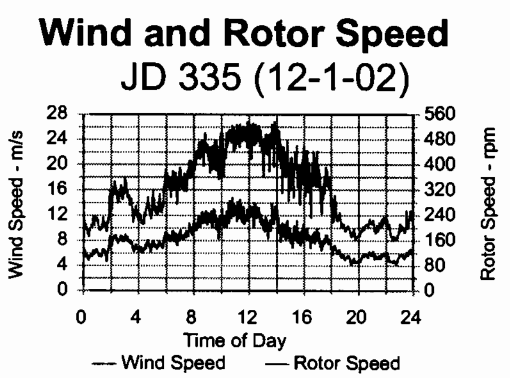


Figure 6. Wind Speed and Wind Turbine Rotor Speed (Dec. 1, 2002).

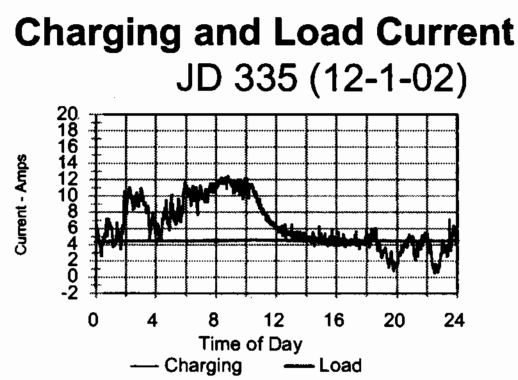


Figure 7. Charging and Load Current (Dec. 1, 2002).

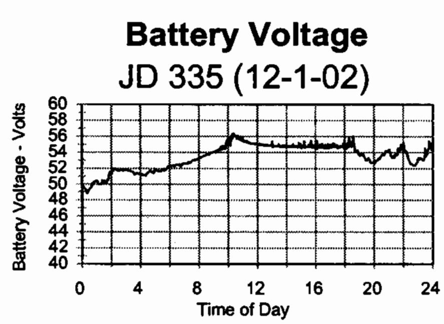


Figure 8. Battery Voltage (Dec. 1, 2002).

Electrical Loading

Four different resistive electrical loads were evaluated for this battery charging wind system – 4, 8, 12, and 16 amps. In order to exclude data when the controller was preventing over charging, all data above a battery voltage of 54.5 Volts was excluded. The load current could vary if:

1. another string of lights was turned on
2. one light burned out causing one string of lights to drop out
3. timer was being used since the timer could turn the electrical load on or off on certain days of the week and different times of the day
4. the relay between the batteries and the electrical load disconnected the batteries from the electrical load because of low battery voltage.

Because of the above, then the processing program for binning the data would only bin data over a certain load current range (e.g. for 8 amps the load current range was 7 to 9 amps). Due to buildings located north, northwest, and northeast of the wind turbine, only data from the southerly direction (90 to 270 degrees) were binned. Figure 9 shows the rotor speed of the wind turbine for the four different electrical loadings. The rotor speed peaked at 500 rpm (13.5 m/s wind speed) for the 8 and 12 amp electrical loadings while the 16 amp electrical load peaked at 510 rpm (14.5 m/s wind speed) and the 4 amp electrical load peaked at 440 rpm (12 m/s wind speed). This variance in peak rotor rpm was due to the electrical loading delaying when the wind turbine furled (the higher the electrical loading the higher the furling wind speed). Figure 10 shows how the charging current varied with the electrical loading. It was noticed that the maximum charging current was 12 amps. This is due to the rectifier in the controller not allowing more than 12 amps to go to the battery. One can see that if the electrical loading was always 12 amps or above then the batteries would never be over charged.

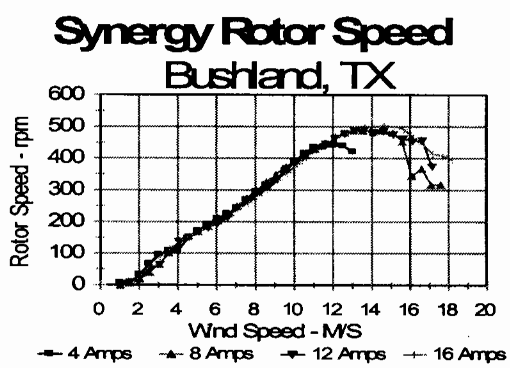


Figure 9. Effect of Electrical Load on Wind Turbine Rotor Speed.

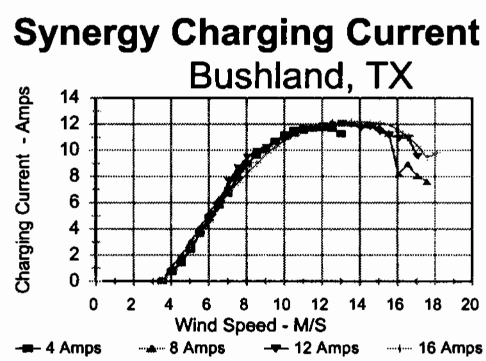


Figure 10. Effect of Electrical Load on Power Coefficient

Figures 11 and 12 show the AC power corrected to sea level, standard day (SLSD) conditions and the power coefficient, respectively. The power was corrected to SLSD conditions by multiplying the AC power by the ratio of the sea level air density (1.225 kg/m^3) to that measured at Bushland. Although this power data corrected to SLSD conditions is good as a reference, it may not be representative of SLSD conditions. This is because the higher air density at SLSD conditions may cause the wind turbine to furl at a lower wind speed. Since the

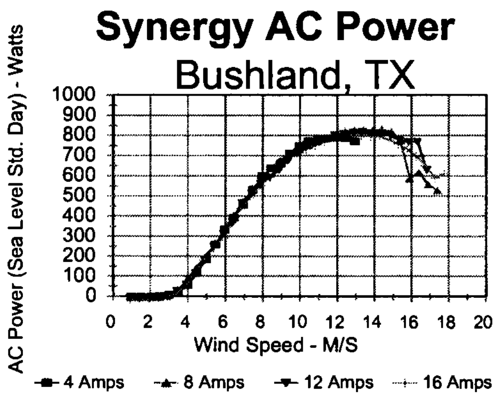


Figure 11. Effect of Electrical Load on AC Power (Corr. to SLSD).

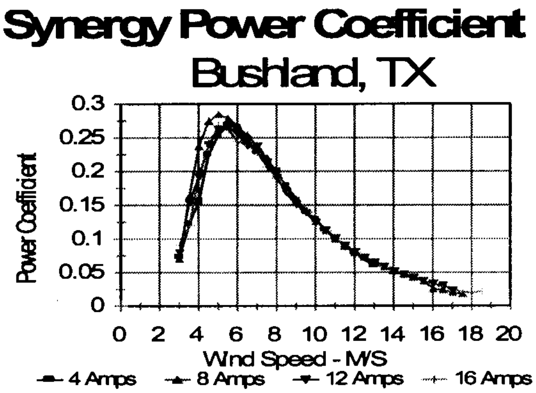


Figure 12. Effect of Electrical Load on Power Coefficient.

Synergy S5000DD PMA efficiency was not measured, the power coefficient shown in Figure 12 is not just the wind turbine rotor efficiency. The power coefficient peaked at approximately 0.275 in a wind speed range of 5 to 6 m/s. The power coefficient of most wind turbines peak in a wind speed range of 7 to 9 m/s, so this wind turbine was obviously designed for low wind speed locations.

AC Power and AC to DC Power Conversion

For a constant electrical load (12 amps), Figure 13 shows the measured DC power, measured AC power, and the AC power corrected to SLSD conditions. The AC cut-in wind speed was 3 m/s, but the DC cut-in wind speed was 3.5 m/s. This is because the controller actually consumes power and it takes about a 3.5 m/s wind speed to offset the controller-consumed power. The peak power for each power curve is 610 Watts (DC measured), 710 Watts (AC measured), and 830 Watts (SDSL conditions). Figure 14 shows the ratio of AC to DC power. At 4 m/s almost 50% of the power is lost converting to DC from AC, but by 7 m/s 87% of the AC power is converted to DC power.

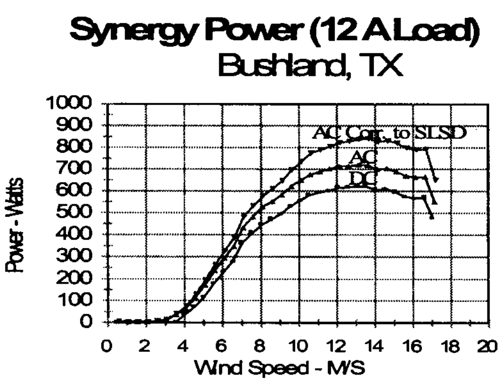


Figure 13. Power Curves at a Constant Electrical Load.

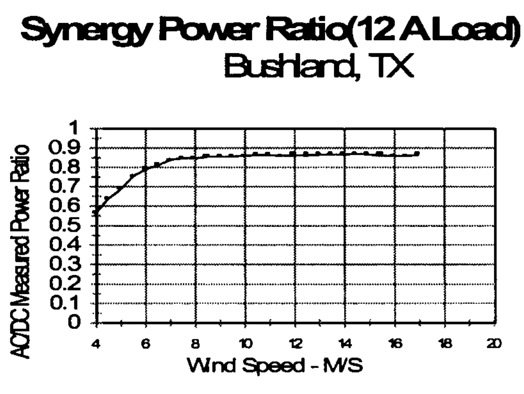


Figure 14. Ratio of AC to DC Power for a Constant Electrical Load.

Energy

Synergy rates their wind turbines by how many kWh they produce using a Rayleigh wind distribution with an average wind speed of 4.5 m/s. Figure 15 shows how many kWh can be expected for each of the power curves shown in Figure 13 with this Rayleigh wind distribution. In addition, the Synergy S5000DD rating is also shown in Figure 15. For SLSD conditions, the wind turbine is shown to produce 4.5 kWh, but Synergy rates the S5000DD at 5 kWh. For the elevation at Bushland, TX of 1159 m (3800 ft), the Synergy S5000DD generated 4.1 kWh/day of AC energy and 3.2 kWh/day of usable DC energy.

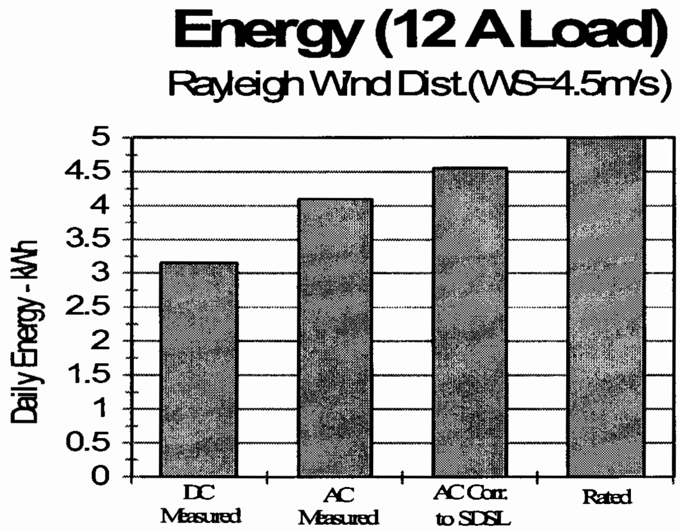


Figure 15. Daily Energy Produced at a Constant Electrical Load

CONCLUSIONS

The Synergy S5000DD has been charging batteries and supplying power to DC lights for about 1.5 years. The controller has been successful in preventing the batteries from being overcharged. To keep the batteries from being discharged excessively, it was necessary to install a voltage relay between the batteries and the electrical load and a quick disconnect switch between the controller and the batteries.

Several electrical loadings (200W – 800W) were tested on this battery charging system. The AC power and charging current were independent of the electrical load except at higher wind speeds. As the electrical loading was increased, the wind speed at which furling would occur also increased. For an 8 or 12 amp load, furling began occurring at a 13.5 m/s wind speed.

The power curve (corrected to SLSD conditions) was 10% below Synergy's rating. For wind speeds above 7 m/s there was a loss of about 13% in converting the AC power to usable DC power. The peak power coefficient occurred in a wind speed range of 5 to 6 m/s and that indicated this wind turbine was designed for low wind speeds.

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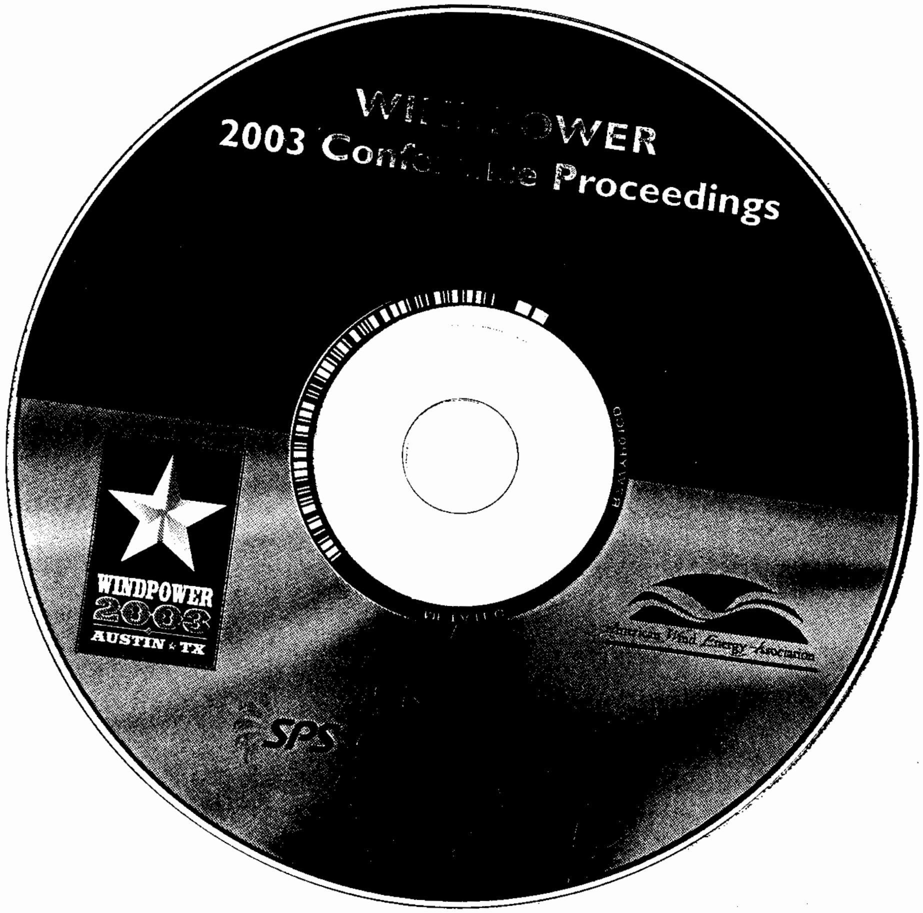
REFERENCES

1. 1987. Todd, R. W. "Controls For Small Wind/Solar/Battery Systems", Wind Engineering, Vol. 11. No. 3, pp. 124-130.
2. 1995. Drouilhet, S. et al, "Optimizing Small Wind Turbine Performance in Battery Charging Applications", Windpower 1995, Washington D.C., pp. 403-413.
3. 1995. Manwell, J.F. et al, "Recent Progress in Battery Models for Hybrid Wind Power Systems", Windpower 1995, Washington D.C., pp. 415-424.
4. 1995. Perahiz, J. and Nayar, C.V. "Model and Simulation of a Wind Turbine Powered Permanent Magnet Alternator Battery Charging System", Wind Engineering, Vol. 19, No. 6, pp. 303-324.
5. 1996. Muljadi, E. et al, "Analysis of Wind Power for Battery Charging", Energy Week '96, Book VIII, Houston, TX, pp. 190-195.
6. 1998. Gevorgian, V. et al, "Modeling, Testing and Economic Analysis of Wind-Electric Battery Charging Station", Windpower 1998, Bakersfield, CA, pp. 119-128.
7. 1999. Corbus, D. et al, "Small Wind Turbine Testing and Applications Development", Windpower 1999, Burlington, VT, CD-ROM.
8. 2000. Gevorgian, V. et al, "Development and Testing of Commercial Prototype Wind-Electric Battery Charging Station", Windpower 2000, Palm Springs, CA CD-ROM.
9. 2001. Perakia, J. and Nayar, C.V., "Simulation of a Wind Powered Wound Rotor Induction Generator with Slip Power Recovery for Battery Charging", Wind Engineering, Vol. 25, No. 2, pp. 81-104.
10. 2002. Corbus, D. et al, "Battery Voltage Stability Effects on Small Wind Turbine Energy Capture", Windpower 2002, Portland, OR, CD-ROM.



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